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UNITED STATES LETTERS PATENT

FOR

APPARATUS AND METHOD OF CONTROLLING MOTION AND VIBRATION OF AN NMR SENSOR IN A DRILLING BHA

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Cross Reference to Related Applications

This application claims the benefit of U.S. Provisional Application No. 60/453,438, filed March 10, 2003.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to determining geological properties of subsurface formations using MWD/LWD sensors, and particularly for improving the accuracy of signals from such sensors by restricting the tool motion during the measurements.

Description of the Related Art

A variety of techniques are utilized in determining the presence and estimation of quantities of hydrocarbons (oil and gas) in earth formations. These methods are designed to determine formation parameters, including among other things, the resistivity, porosity and permeability of the rock formation surrounding the wellbore drilled for recovering the hydrocarbons. Typically, the tools designed to provide the desired information are used to log the wellbore. Much of the logging is done after the well bores have been drilled. More recently, wellbores have been logged while drilling, which is referred to as measurement-while-drilling (MWD) or logging-while-drilling (LWD).

The various sensors utilized in the MWD/LWD environment are subjected to substantial motion and vibration that can compromise the quality of the resulting measurements. The MWD/LWD sensor sensitivity to motion can be roughly grouped in

three categories: (i) sensors that are not significantly affected such as temperature sensors; (ii) sensors that can not tolerate substantially any motion such as formation pressure sampling systems; and (iii)sensors that produce degraded measurements such as, for example, Nuclear Magnetic Resonance (NMR) systems and other nuclear lithology sensors known in the art.

Nuclear Magnetic Resonance logging tools and methods are used for determining, among other things, porosity, hydrocarbon saturation and permeability of the rock formations. The NMR logging tools are utilized to excite the nuclei of the liquids in the geological formations surrounding the wellbore so that certain parameters such as nuclear spin density, longitudinal relaxation time (generally referred to in the art as T_1) and transverse relaxation time (generally referred to as T_2) of the geological formations can be measured. From such measurements, porosity, permeability and hydrocarbon saturation are determined, which provides valuable information about the make-up of the geological formations and the amount of extractable hydrocarbons.

The NMR tools generate a uniform or near uniform static magnetic field in a region of interest surrounding the wellbore. NMR is based on the fact that the nuclei of many elements have angular momentum (spin) and a magnetic moment. The nuclei have a characteristic Larmor resonant frequency related to the magnitude of the magnetic field in their locality. Over time the nuclear spins align themselves along an externally applied static magnetic field creating a net magnetization. This equilibrium situation can be disturbed by a pulse of an oscillating magnetic field, which tips the spins with resonant frequency within the bandwidth of the oscillating magnetic field away from the static

field direction. After tipping, the spins precess around the static field at a particular frequency. At the same time, the magnetization returns to the equilibrium direction (i.e., aligned with the static field) according to a decay time known as the "spin-lattice relaxation time" or T_1 . For hydrogen nuclei a static field of 235 Gauss would produce a precession frequency of 1 MHz. T1 is controlled totally by the molecular environment and is typically ten to one thousand ms. in rocks.

Tool motion can seriously affect the performance of NMR tools used in an MWD/LWD environment because the measurement is not instantaneous and requires a non-varying magnetic field during the measurement time. NMR tools that have static magnetic fields and that have complete rotational symmetry are unaffected by rotation of the tool since the fields in the region of examination do not change during the measurement sequence. However, any radial or vertical component of tool motion will affect the NMR signal. As discussed in United States Patent 5,705,927 issued to *Kleinberg*, resonance regions of many prior art instruments are of the order of 1 mm. Accordingly, a lateral vibration at a frequency of 50Hz having an amplitude of 1 mm (100 g acceleration) would disable the instrument. The *Kleinberg* '927 patent discloses making the duration of each measuring sequence small, e.g. 10 ms, so that the drill collar cannot be displaced by a significant fraction of the vertical or radial extent of the sensitive region during a measurement cycle. However, using such short measurement times only gives an indication of the bound fluid volume and gives no indication of the total fluid volume.

There are numerous patents discussing the vibration of a rotating shaft subject to mechanical forces of the kind encountered by a drill string. United States Patent 5,358,059 issued to *Ho* discloses the use of multiple sensors, including accelerometers, magnetometers, strain gauges and distance measuring sensors for determining the conditions of a drillstring in a borehole in the earth. The motion of the drill string in the borehole includes rotational motion, transverse(or radial) motion, and a whirl of the drill string. Whirling of the drillstring is the eccentric motion of the axis of the drillstring around the axis of the borehole and is a motion of great concern in NMR measurements. In an NMR tool, this motion causes the magnetic field strength in the region of examination to change with time, thereby degrading the measurement signal. Both whirl and various vibrational bending modes can cause radial motion that degrades the measurement.

The methods and apparatus of the present invention overcome the foregoing disadvantages of the prior art by providing a system for limiting the motion of the drill string in the region of measurement.

SUMMARY OF THE INVENTION

The present invention contemplates a system for controlling sensor motion during a measurement comprising a drilling assembly in a wellbore, where the drilling assembly has a drill bit at one end and is engaged with a drilling tubular at an opposite end thereof. A first sensor is disposed in the drilling assembly for making a measurement of a formation parameter of interest. A substantially non-rotating stabilizer is disposed in the

drilling assembly proximate the first sensor. The substantially non-rotating stabilizer is adapted to reduce motion of the first sensor below a predetermined level during the measurement.

In another aspect, a method for controlling sensor motion during a measurement, comprises extending a drilling tubular in a wellbore to a downhole location. The drilling tubular is engaged with a drilling assembly having a drill bit at a bottom end thereof. A first sensor disposed in the drilling assembly is used for making a measurement of a formation parameter of interest. A non-rotating stabilizer is attached in the drilling assembly proximate the first sensor. The non-rotating stabilizer is adapted to reduce motion of the first sensor below a predetermined level during the measurement.

Examples of the more important features of the invention thus have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

Figure 1 is a schematic drawing of a drilling assembly according to one embodiment of the present invention;

Figure 2 is a schematic drawing of the vibrational motion of a drill string according to one embodiment of the present invention;

Figure 3A is a schematic drawing depicting the whirling motion of a drill string in a borehole according to one embodiment of the present invention;

Figure 3B, 3C are schematic drawings depicting the effects of a rotating stabilizer on the whirling motion of a drill string in a borehole according to one embodiment of the present invention;

Figure 4A is a schematic drawing of a non-rotating stabilizer according to one embodiment of the present invention;

Figure 4B is a schematic drawing of an end view of a non rotating stabilizer in a borehole according to one embodiment of the present invention;

Figure 5 is a schematic drawing of force diagram showing forces associated with a non-rotating stabilizer in a borehole according to one embodiment of the present invention;

Figure 6 is a schematic drawing of an eccentric non-rotating stabilizer according to one embodiment of the present invention; and

Figure 7 is a schematic drawing of a drilling assembly having an adjustable non-rotating stabilizer according to one embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to **FIG. 1**, an exemplary drilling assembly **100** at the end of a drilling tubular such as, for example, drill string **102** or, alternatively, coiled tubing (not shown) is illustrated in a borehole **50**. A measurement-while-drilling (MWD) tool **104**, an associated pulsed nuclear magnetic resonance (NMR) tool **112** with NMR sensor **113** electronic circuitry **124**, and a pulsed power unit **118** are connected in tandem in the drilling assembly **100**. The MWD tool **104** may also have other sensors (not shown) including, but not limited to, a sonic sensor, a density measurement tool, and a porosity measurement tool. A communication sub (not shown) using, for example, two-way telemetry, is also provided in the drilling assembly **100**. The drilling assembly is also provided with a plurality of motion sensors (not shown) for sensing the motion of the tool within the borehole. In one embodiment of the invention, the motion sensors are accelerometers that sense the three components of acceleration of the tool.

The drilling assembly **100** also includes a drill bit **106**. The drill string **102** includes, for example, sections of drill pipe connected end-to-end or a generally continuous coiled tubing. The drill bit **106** may be rotated by rotating the drill string **102**. Alternatively, a downhole motor (not shown) may be included in the drill string **102** and/or the drilling assembly **100** for rotating the drill bit **106**. The borehole **50** typically contains a drilling fluid **122,** also called "mud", which is forced through the drill string **102** and the bottom hole drilling assembly **100** through the drill bit **106**. The drilling

fluid acts to lubricate the drill bit **106** and to carry borehole cutting or chips away from the drill bit **106**.

The communication sub and power unit **118**, MWD tool **104**, and NMR tool **112** with sensor **113** are all connected in tandem with the drill string **102**. Such subs and tools form a bottom hole drilling assembly **100** between the drill string **102** and the drill bit **106**. Non-rotating stabilizers **126, 127** are used to stabilize and center the drilling assembly **100** and create a vibrational node within the borehole. The housing **114**, for example, a drilling collar, is made of a nonmagnetic alloy. The drilling assembly **100** makes various measurements including pulsed nuclear magnetic resonance measurements while the borehole is being drilled. The NMR tool is rotationally symmetric about a longitudinal axis **128** of the drilling assembly **100**. For a more detailed description of an exemplary NMR tool, see US Patent No. 6,459,263 B2 to Hawkes et al., assigned to the assignee of this application, and incorporated herein by reference.

The motion of the drill string **102** and the bottom hole drilling assembly **100**, without the presence of a stabilizer, can include the superposition of eccentric whirl and various modes of lateral (also called radial) vibrational movement. The resulting lateral motion may result in a excessive lateral displacement and velocity close to the NMR sensor resulting in a substantially degraded NMR signal. The addition of a stabilizer near the sensor position acts to centralize the drilling assembly **100** and to substantially act as a vibrational node, restricting the allowable lateral movement and velocity of the drilling assembly at that location. This effect can be seen in **Figure 2** which shows the

analytically predicted vibrational motion **201** of the drilling assembly and the motion at node **202** indicating the effect of the stabilizer near the sensor.

The use of a fixed diameter, rotating stabilizer, common in the art, has several drawbacks in this application. A fixed diameter, rotating stabilizer has to have an outside diameter substantially smaller (3-4mm) than the nominal borehole diameter. The common tendency is for the borehole to become slightly oversize resulting in a lateral motion caused by vibration and/or whirl of even more than the nominal 3-4mm clearance. Analysis of NMR measurements indicate that motion amplitudes greater than about 1-2mm result in strongly degraded results using such sensors. **Figure 3A** shows an end view of the whirl of the sensor housing **114** in the borehole **50**. The center **301** of the sensor housing **114** moves along the path **303**, with radius **304**, around the center **302** of the borehole **50** degrading sensor measurements. Radius **304** is substantially greater than the allowable motion for acceptable measurements. The addition of fixed diameter, rotating stabilizer **226**, with centralizer ribs **226a-c**, near the sensor housing **114** reduces the whirl of the sensor housing **114** but not enough to provide acceptable measurements because of the difference in diameters discussed above, see **Figures 3B-3C**. The interaction of the rotating centralizer ribs with the wall of the borehole can result in a tendency for the centralizer to crawl around the internal diameter of the borehole **50**. In addition, the additional mass of the rotating stabilizer, moving eccentrically around the center **302** of borehole **50** act as unbalanced rotating masses that tend to excite additional vibration modes.

According to one embodiment of the present invention (see **Figures 1, 4A, 4B**), a non-rotating stabilizer **426** is inserted in the drilling assembly **100** near the NMR sensor **113**. As used herein, non-rotating means that the portions of the stabilizers contacting the wall of the borehole do not rotate relative to the borehole. Stabilizer **426** has a sleeve **428** mounted to a body **427** through bearings **430**. Sleeve **428** has ribs **428a-c** attached thereto for centralizing the drilling assembly in borehole **50**. The ribs **428a-c** contact the wall of borehole **50** and do not rotate when the drill string **102** rotates the drilling assembly **100** to rotate drill bit **106**. As seen in **Figure 4B** the drilling assembly weight W, in a deviated wellbore, is supported by the ribs **428b,c**. This tends to create a substantial friction that resists rotational motion between the between the ribs and the wall of the borehole. The only torque trying to cause rotation of the non-rotating sleeve **428** is the relatively small frictional torque of the bearings **430**. Bearings **430** may be sleeve bearings or alternatively anti-friction rolling element bearings. The bearings may be oil lubricated. Alternatively, the bearings may be mud lubricated. Note that, in any case, the relatively low bearing frictional torque acts at the bearing diameter which is a smaller diameter than the outer rib diameter where the rib-borehole friction is applied. Therefore, the sleeve **428** does not rotate relative to the wall of the borehole while the drill string **102** and the rest of the drilling assembly rotates. The non-rotating sleeve **428** constrains the NMR sensor proximate the stabilizer **426**, to rotate substantially concentrically about the axis **401** of the non-rotating sleeve **428**, thereby eliminating whirl effects in the NMR sensor measurements. It is also clear from the force diagram of **Figure 5** that the weight of the drilling assembly is transmitted through the ribs to the wall of the borehole **50**. There is a

horizontal component of this force equal to W/2 cos(θ) that is reacted at the wall of the borehole. This horizontal force must be exceeded by any radial vibration force in order to create lateral motion that will affect sensor measurements. Therefore, the non-rotating stabilizer also acts to reduce the radial motion caused by drill string vibration. As seen in **Figure 1**, the drilling assembly may also include a second non-rotating stabilizer **127** positioned such that NMR sensor is between two such non-rotating stabilizers. As one skilled in the art will appreciate, such a two-point support arrangement acts to further limit any bending displacement at the sensor location.

It can be seen from **Figure 5** that the magnitude of the horizontal force increases as θ decrease since the cosine function approaches one as the θ approaches zero. In one embodiment, see **Figure 6**, the center of rotation of the drilling assembly **100** in the non-rotating stabilizer is eccentrically located below the center **501** of the stabilizer blades. As shown above, this arrangement increases the horizontal forces that will counter act any lateral vibration motion.

In another embodiment, see **Figure 7**, an adjustable stabilizer **727** is inserted in drilling assembly **700**. Adjustable stabilizer **727** has an adjustable rib **728** that extends to contact the wall of the borehole **50** to substantially eliminate any clearance at that location. Alternatively, adjustable stabilizer **727** may have multiple adjustable ribs **728**. The adjustable rib **728** supplies sufficient force to overcome any vibrational motion at that location, thereby further reducing the motion at the sensor location to acceptable levels. The adjustable rib **728** may be powered by a hydraulic system or an electric motor contained in the stabilizer **727**. Measurements of radial motion from

accelerometers in the stabilizer **727** or the MWD tool **104**, for example, may be used by a downhole controller including a processor (not shown) to control the displacement of the adjustable rib **728** to increase the effective diameter of the stabilizer **727** until the motion of the sensor **113** is within acceptable levels. Alternatively, two adjustable stabilizers may be inserted in drilling assembly **100** on either side of sensor **113**. Alternatively, the adjustable rib **728** described above may be a pivoted arm (not shown) that is extendable to contact the wall of borehole **50**.

The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiment set forth above are possible. It is intended that the following claims be interpreted to embrace all such modifications and changes.